

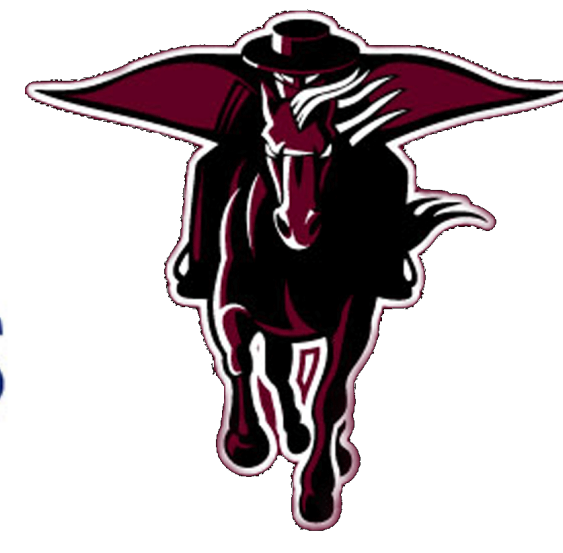
# Statistical analysis of historical GLOBE aerosol optical thickness data

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## Background

The GLOBE Aerosol Protocol requires that students make an observation of sky color and visibility along with an aerosol optical thickness (AOT) measurement. How to observe sky color and visibility is not explicitly stated in the Aerosol Protocol, but directions can be found in the Observing Visibility and Sky Color Protocol. According to the protocol, to determine sky color, “The darkest part of the sky can often be seen about half way between the horizon and directly overhead, in the ‘anti-sun’ direction – that is, when you look at the sky with your shadow in front of you. Students should try to locate the darkest (bluest) color of the sky and record the sky color.” Students can determine visibility, “by looking at the same scene or object every day students will gradually develop a sense of whether the day is unusually clear, clear, somewhat hazy, very hazy, or extremely hazy.” (GLOBE, 2005). While both of these observations are subjective, sky color and visibility observations should become more reliable and consistent over time. According to the protocol, observations for sky color and visibility should fall along the diagonal line in the “Visibility and Sky Color Summary Chart” (Table B1). This is represented in **green** on Table B1. Also, in the Aerosol Protocol, there is a relationship between AOT and sky conditions in a discrete range, although it is stated as an approximate and varied by local conditions (Table B2). There has been discussion about being able to determine AOT based on sky color, by means of the human eye or an app-based program. A 2014 International Space Apps Challenge entitled “My Sky Color” proposed that a method could be developed in which a smartphone camera could quantitatively assess AOT using sky color protocols. (Space Apps, 2014). The feasibility of relating sky conditions (sky color and visibility) with AOT was statistically analyzed using historical GLOBE data. Since the GLOBE dataset spans over a decade and has sky color and visibility reported with each AOT measurement, it was ideal for the analysis in this study.

Table B1. Visibility and sky color summary chart

Visibility / Sky Color	Deep Blue	Blue	Light Blue	Pale Blue	Milky
Unusually Clear					
Clear					
Somewhat Hazy					
Very Hazy					
Extremely Hazy					

Table B2. Relationship between AOT and visibility condition

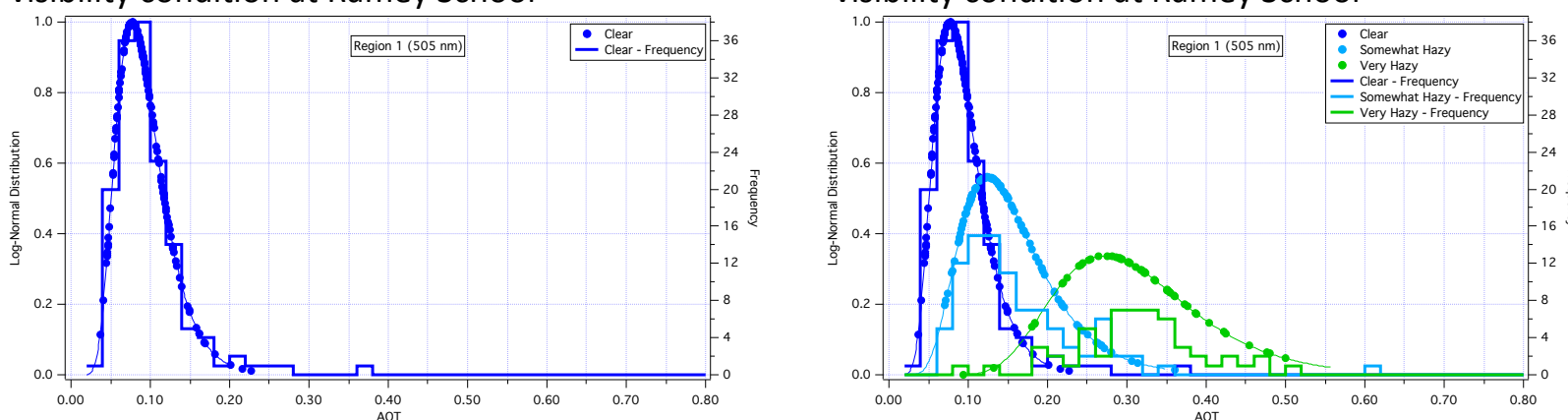
Sky Condition	Green Channel (505 nm)
Unusually Clear	0.03-0.05
Clear	0.05-0.10
Somewhat Hazy	0.10-0.25
Very Hazy	0.25-0.50
Extremely Hazy	>0.50

## Methods and Analysis

A set of criteria was applied to the Ramey School (Aguadilla, Puerto Rico) dataset in order to develop a statistical analysis. First, AOT measurements were separated into three categories based on the sky color and visibility observations. These three categories are “Sky Color”, “Visibility”, and “Matched Pair”. “Matched Pair” is defined as observations that fell along the diagonal in Table B1. For sky conditions in each category, a histogram with an interval of 0.02 AOT units was applied to each bin. The mean ( $\mu$ ) and standard deviation ( $\sigma$ ) were calculated for each sky condition, and data points  $>3\sigma$  from the mean were removed from the analysis. A log-normal distribution was applied to each condition with  $>30$  AOT measurements. The histogram for the AOT measurements with the clear visibility condition appears to follow a log-normal distribution (Graph M1). The histogram for the somewhat hazy visibility condition also follows a log-normal distribution, but this distribution appears to be less applicable to the very hazy visibility condition, as there are significantly fewer aerosol measurements that span a larger range of AOT values when compared to the clear and somewhat hazy visibility conditions (Graph M2). Lastly, data in each category were normalized between 0 and 1 in order to compare distributions between each site and region.

Once the statistical analysis method was developed, data from sites with  $>100$  aerosol measurements were requested from GLOBE. There were 26 sites that met this requirement, of which 22 were used in the analysis. Data (AOT, sky color, and visibility) from each site were separated into five distinct geographical regions based on latitude in 10-degree intervals (Table M1). The statistical analysis was only completed for the green channel (505 nm), although the same method could also be applied to the red channel (625 nm).

Graph M1. Distribution of AOT for the clear visibility condition at Ramey School



Graph M2. Distribution of AOT for each visibility condition at Ramey School

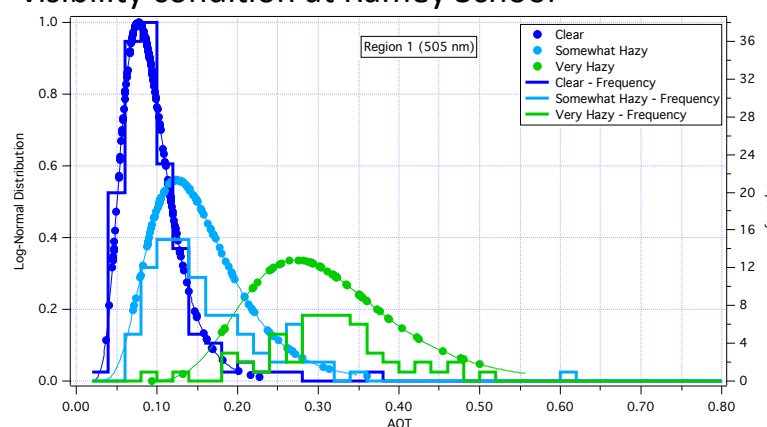


Table M1. Number of sites and AOT measurements in each geographical region

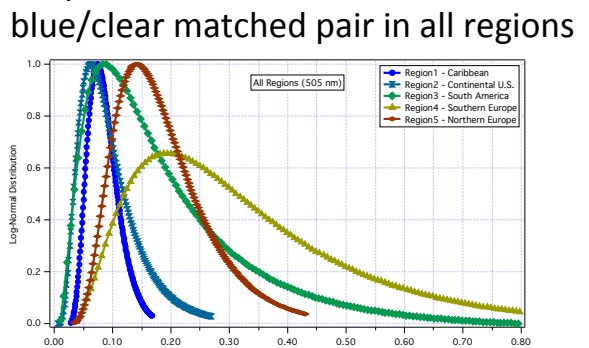
Region	Classification	# of sites	# of AOT measurements
1	Caribbean	1	329
2	Continental U.S.	8	1418
3	South America	2	699
4	Southern Europe	3	413
5	Northern Europe	8	1036

\*In Tables R1-R5, **green** indicates the sky color and visibility pairing in which the greatest number of measurements were made. **Yellow** indicates all other pairings in which  $>10$  measurements were made.

## Conclusion

In each region, between 67%-83% of the observational sky color and visibility data fell into four paired conditions, clear/blue, clear/light blue, somewhat hazy/blue, and somewhat hazy/light blue (“the box”). While it is certainly possible that a majority of observations would fall into these four paired conditions, AOT values for sky color, visibility, and matched pair categories were reported in a much larger range than would be expected based on the GLOBE Aerosol Protocol. For the clear visibility condition in particular, where a majority of observations were reported in each of the regions, the standard deviation of AOT measurements ranges from 0.03 in Region 1 to 0.21 in Region 4 (Table R11-R15). At least three of the five regions did not have  $>30$  measurements in the sky color conditions deep blue and milky or the visibility conditions unusually clear, very hazy, and extremely hazy, which could be attributed to a majority of observations being found in “the box” (Tables C1-C3). By establishing a matched pair, the range of AOT values decreased or stayed the same when compared with the visibility conditions in Region 1, Region 2, and Region 4. Initially, this approach was anticipated to produce a more reliable range as a majority of observations should be in a matched pair category. However, due to a limited number of measurements in most sky conditions, only the blue/clear matched pair was able to be established in each region (Graph C1). Other than the range of AOT values established in the Caribbean, which nearly matches the estimated range of AOT values in the GLOBE Aerosol Protocol, it would be difficult to significantly predict a range of AOT values based on sky color or visibility observations alone (Table C4).

Graph C1. Distribution of AOT for each blue/clear matched pair in all regions



Tables C1, C2, C3. Summary of range of AOT values for each sky color, visibility, and matched pair condition in all regions

Sky Color	Caribbean	Continental U.S.	South America	Southern Europe	Northern Europe	
Deep Blue	-	0.04-0.13	-	-	-	
Blue	0.06-0.11	0.04-0.16	0.04-0.43	0.16-0.58	0.11-0.30	
Light Blue	0.07-0.20	0.05-0.27	0.04-0.32	0.10-0.39	0.12-0.42	
Pale Blue	0.15-0.35	0.08-0.48	0.10-0.41	-	0.20-0.51	
Milky	0.29-0.53	-	-	-	0.11-0.39	
Visibility	GLOBE Protocol	Caribbean	Continental U.S.	South America	Southern Europe	Northern Europe
Unusually Clear	0.03-0.05	-	0.03-0.14	0.04-0.36	-	0.08-0.26
Clear	0.05-0.10	0.06-0.13	0.03-0.19	0.03-0.24	0.13-0.54	0.11-0.34
Somewhat Hazy	0.10-0.25	0.09-0.22	0.04-0.26	0.13-0.46	0.11-0.50	0.18-0.43
Very Hazy	0.25-0.50	0.23-0.39	0.07-0.32	-	-	-
Extremely Hazy	>0.50	-	0.08-0.37	-	-	-
Matched Pairs	Caribbean	Continental U.S.	South America	Southern Europe	Northern Europe	
Deep Blue/Unusually Clear	-	-	-	-	-	
Blue/Clear	0.06-0.11	0.04-0.16	0.03-0.43	0.15-0.57	0.11-0.27	
Light Blue/Somewhat Hazy	0.09-0.22	0.04-0.27	-	0.12-0.41	0.18-0.46	
Pale Blue/Very Hazy	0.22-0.37	-	-	-	-	
Milky/Extremely Hazy	-	-	-	-	-	

Table C4. Range of AOT values for each blue/clear matched pair in all regions and comparison with the GLOBE Aerosol Protocol

Blue/Clear	Range
GLOBE Protocol	0.05-0.10
Caribbean	0.06-0.11
Continental U.S.	0.04-0.16
South America	0.03-0.43
Southern Europe	0.15-0.57
Northern Europe	0.11-0.27

## About the Author

Robert Bujosa started working with the GLOBE Program during Summer 2014 as an intern at NASA Langley Research Center under the direction of Dr. Margaret Pippin. After he was comprehensively trained on GLOBE Atmospheric Protocols, he and two other interns evaluated the GLOBE sun photometer and Caltoo sun photometer by making comparisons with the local AERONET instrument. During his internship, he also worked extensively with the Long-term Engagement in Authentic Research with NASA (LEARN) Project, in which a cohort of teachers across the country participated in guided yearlong research projects with their students. This experience with the GLOBE Program and NASA Langley Research Center influenced Robert to enter the field of education, and he now teaches Chemistry and Aquatic Science at Northbrook High School in Houston, TX.

## Acknowledgements

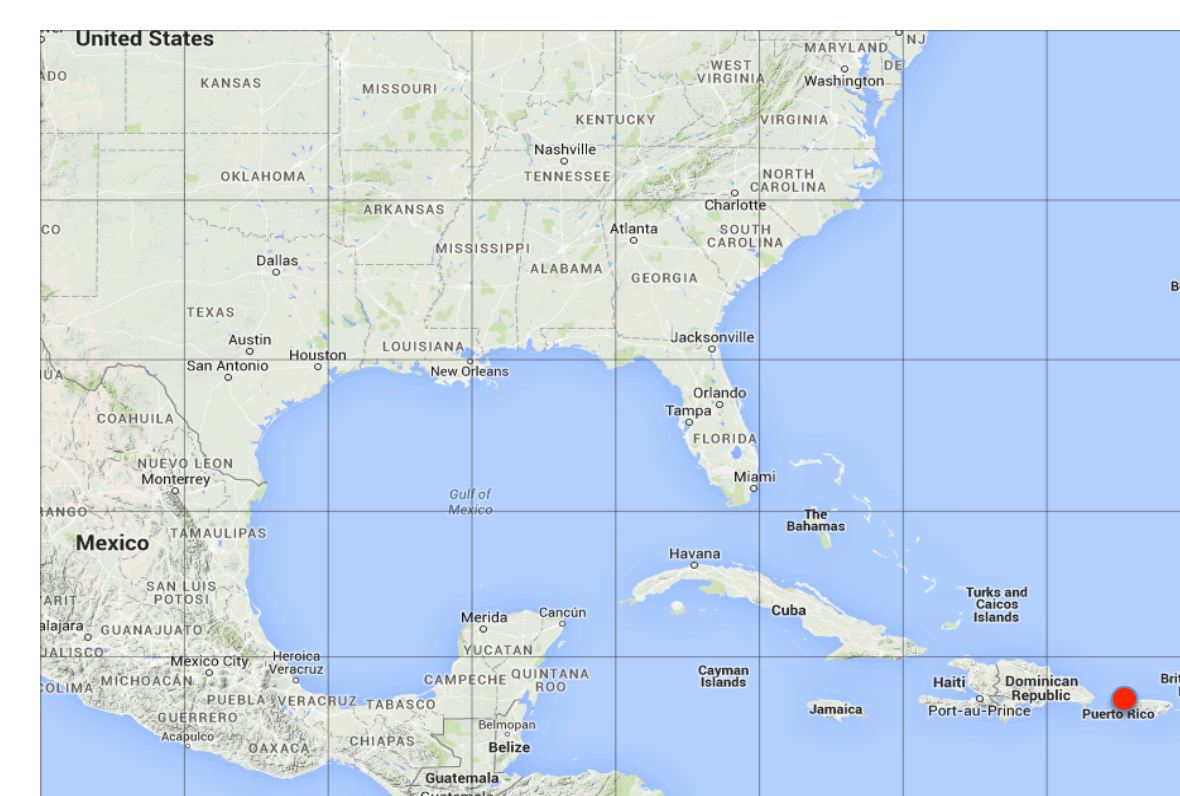
The author would like to thank Dr. Margaret Pippin for providing extraordinary mentorship in atmospheric science and science education during the last two years. This work was supported by the Long-term Engagement in Authentic Research with NASA (LEARN) Project, the Tropospheric Emissions: Monitoring of Pollution (TEMPO) Student Collaboration, and the GLOBE Program with funding provided through the NASA Science Mission Directorate.

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GLOBE. (2005). Observing visibility and sky color protocol. Atmosphere. Retrieved from <https://mynasadata.larc.nasa.gov/docs/hazyskies.pdf>  
Space Apps. (2014). My Sky Color. Space Apps Challenge. Retrieved from <https://2014.spaceappschallenge.org/challenge/my-sky-color/>

## Region 1

### Region Classification: Caribbean



Sites: Ramey School (located in Puerto Rico)

Table R1. Number of measurements for each sky color and visibility pairing in Region 1

Sky Color/Visibility	Deep Blue	Blue	Light Blue	Pale Blue	Milky
Unusually Clear	1	4	0	0	0
Clear	1	89	55	3	0
Somewhat Hazy	0	7	69	17	1
Very Hazy	0	1	4	30	19
Extremely Hazy	0	0	0	2	26

Graph R1. Distribution of AOT for each sky color condition in Region 1

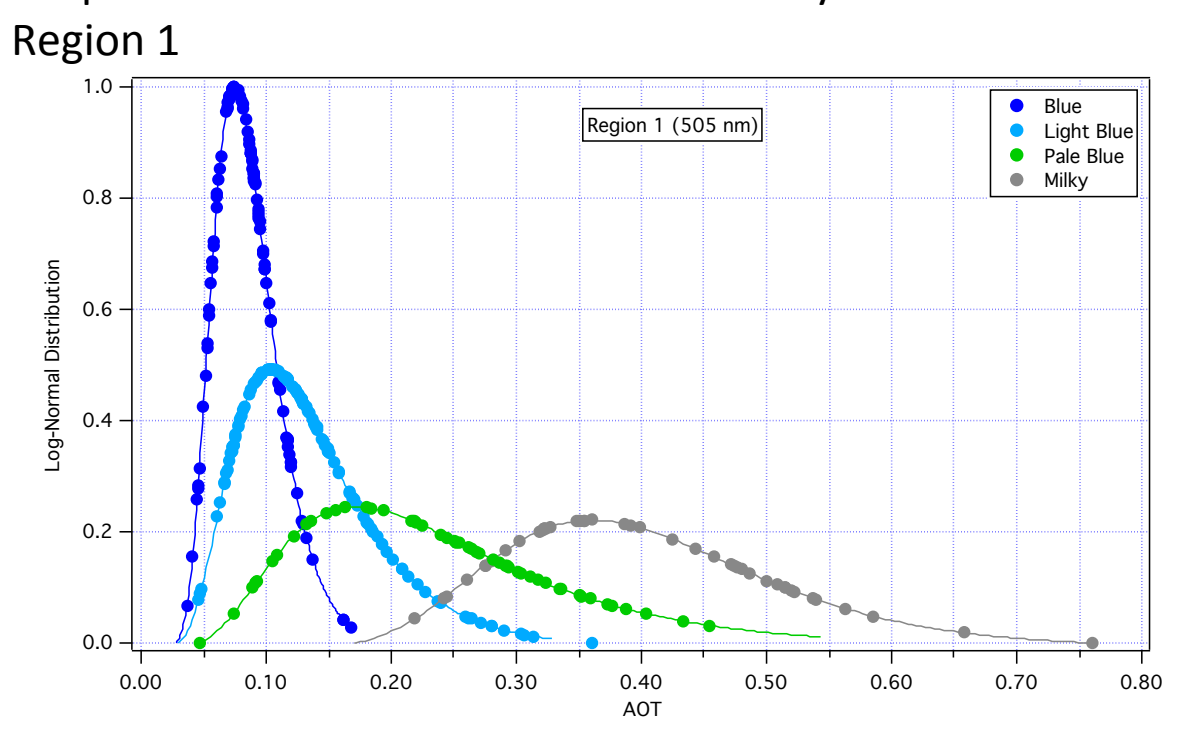


Table R6. Mean, standard deviation, and range for each sky color condition in Region 1

	$\mu$	$\sigma$	Range
Deep Blue	0.09	0.03	0.06-0.11
Blue	0.14	0.06	0.07-0.20
Light Blue	0.25	0.10	0.15-0.35
Pale Blue	0.41	0.12	0.29-0.53

Graph R6. Distribution of AOT for each visibility condition in Region 1

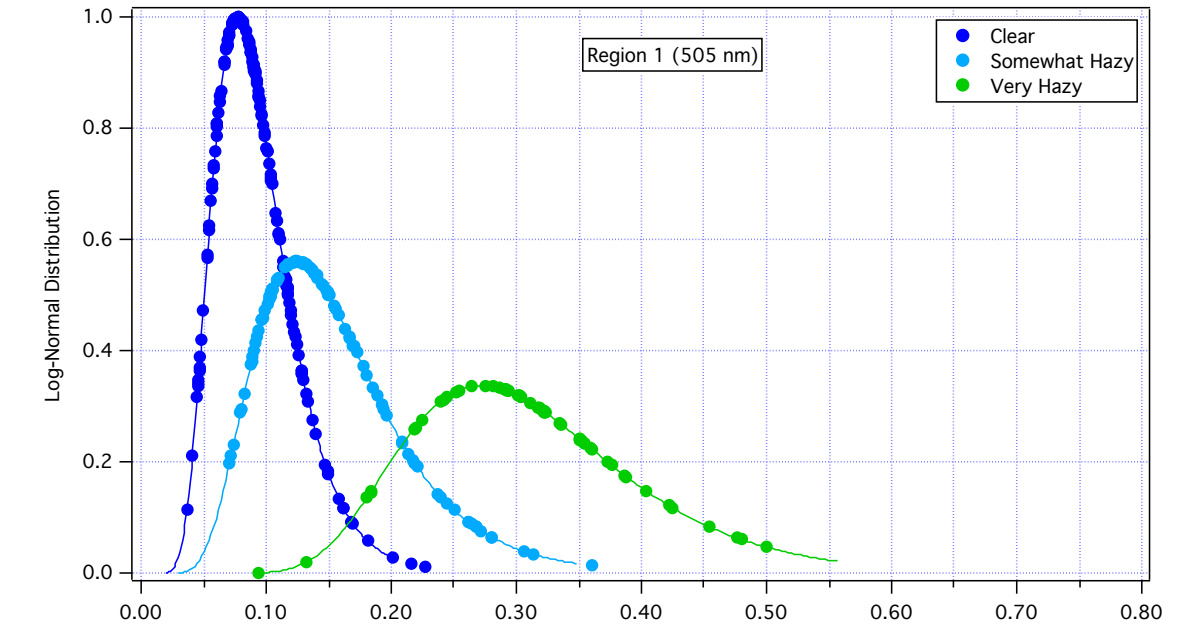


Table R11. Mean, standard deviation, and range for each visibility condition in Region 1

	$\mu$	$\sigma$	Range
Unusually Clear	0.09	0.03	0.06-0.13
Clear	0.11	0.09	0.03-0.19
Somewhat Hazy	0.15	0.11	0.04-0.26
Very Hazy	0.19	0.13	0.07-0.32
Extremely Hazy	0.23	0.15	0.08-0.37

Graph R11. Distribution of AOT for each matched pair in Region 1

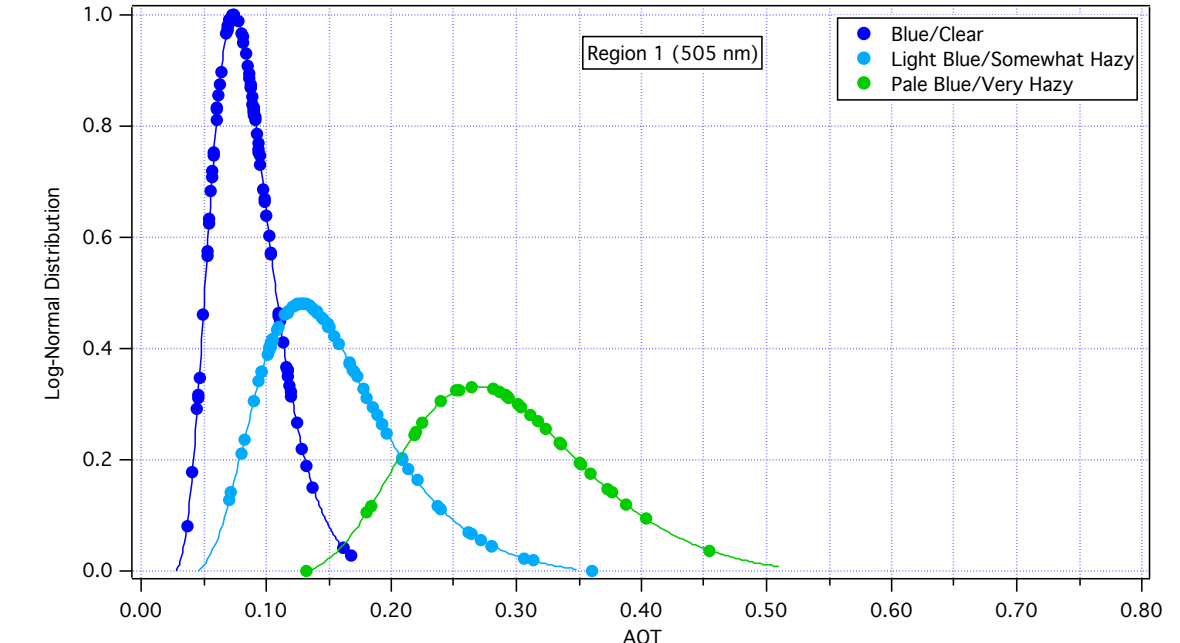


Table R16. Mean, standard deviation, and range for each matched pair in Region 1

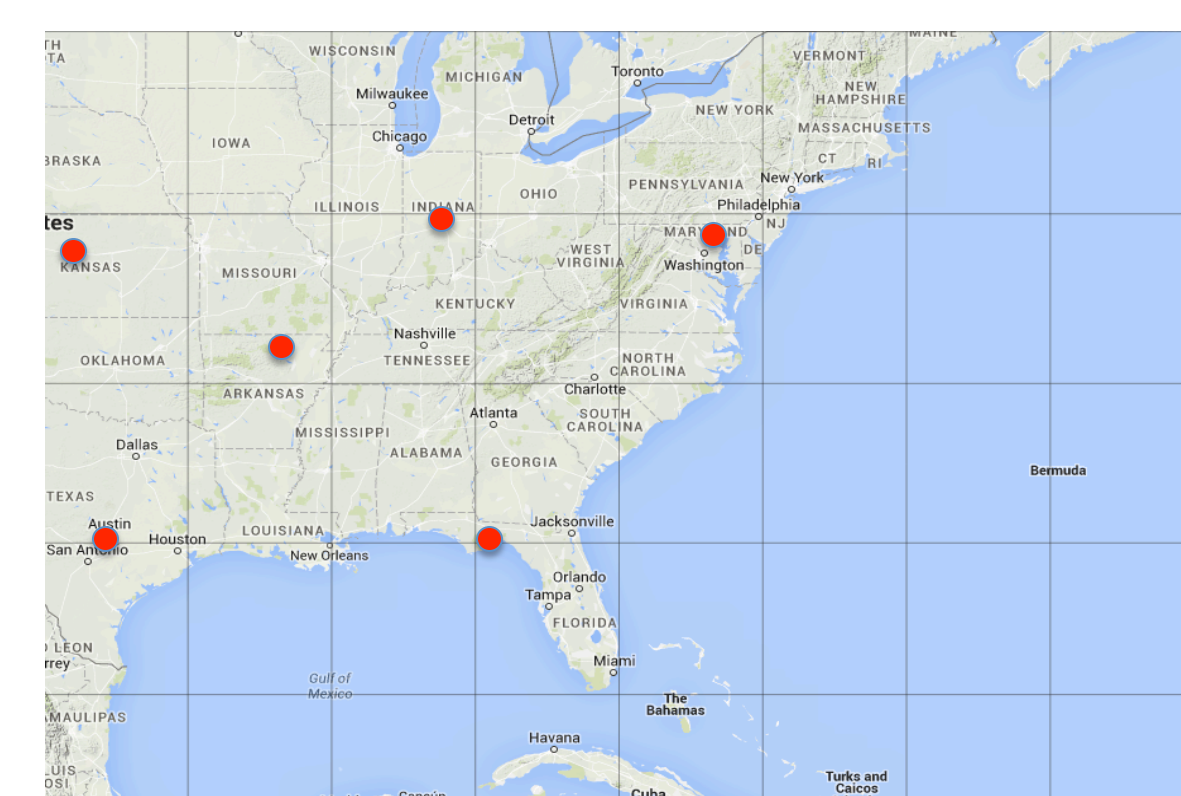
	$\mu$	$\sigma$	Range
Deep Blue/Unusually Clear	-	-	-
Blue/Clear	0.09	0.03	0.06-0.11
Light Blue/Somewhat Hazy	0.15	0.06	0.09-0.22
Pale Blue/Very Hazy	0.30	0.07	0.22-0.37
Milky/Extremely Hazy	-	-	-

### Region 1 Summary:

65% of data in matched pair category  
45% of data in clear visibility condition  
67% of data in clear/blue, clear/light blue, somewhat hazy/blue, and somewhat hazy/light blue paired conditions (“the box”)

## Region 2

### Region Classification: Continental U.S.



Sites: Texas State University, Florida State University Department of Meteorology, Norfolk Elementary School, Norfolk Rebels 4-H Club, Norfolk Passive Irrigation Experiment, Ft. Hays State University, Waynesboro Senior High School, Indiana School for the Deaf (located in USA)

Table R2. Number of measurements for each sky color and visibility pairing in Region 2

Sky Color/Visibility	Deep Blue	Blue	Light Blue	Pale Blue	Milky
Unusually Clear	11	47	4	0	0
Clear	25	653	151	15	4
Somewhat Hazy	1	134	218	22	7
Very Hazy	0	5	51	25	8
Extremely Hazy	0	3	7	22	5

Graph R2. Distribution of AOT for each sky color condition in Region 2

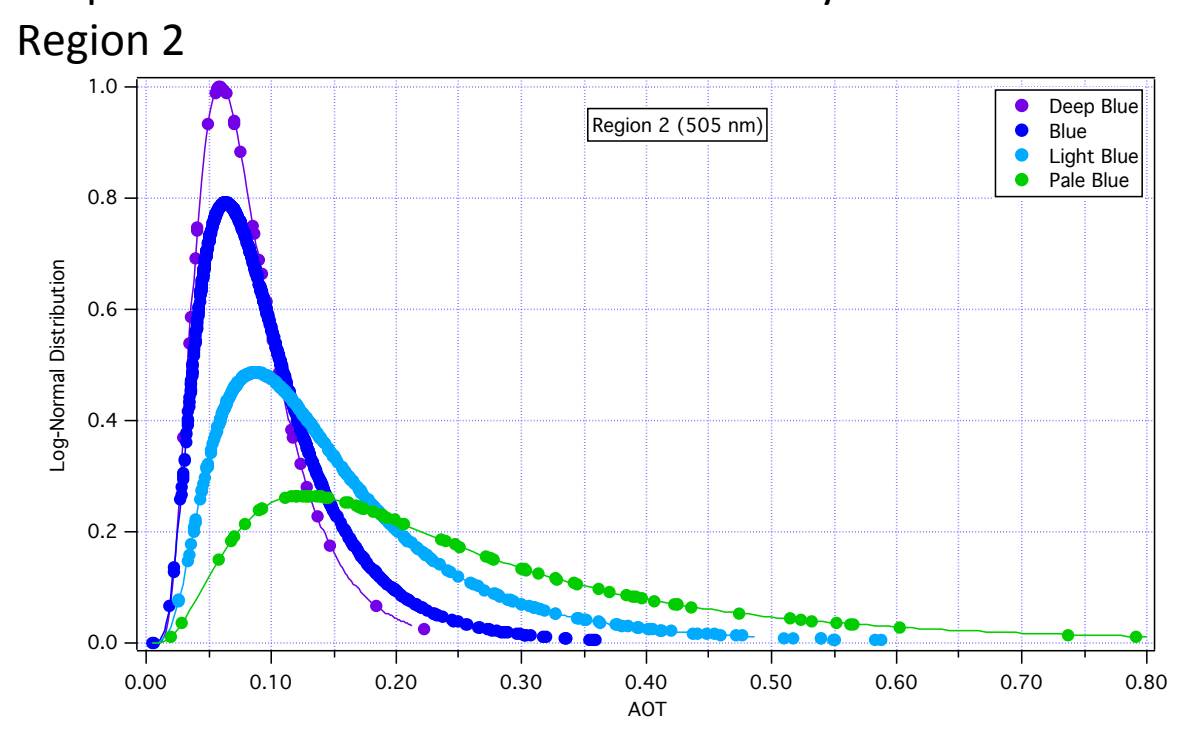


Table R7. Mean, standard deviation, and range for each sky color condition in Region 2

	$\mu$	$\sigma$	Range
Deep Blue	0.08	0.04	0.04-0.13
Blue	0.10	0.06	0.04-0.16
Light Blue	0.16	0.11	0.05-0.27
Pale Blue	0.28	0.20	0.08-0.48
Milky	-	-	-

Graph R7. Distribution of AOT for each visibility condition in Region 2

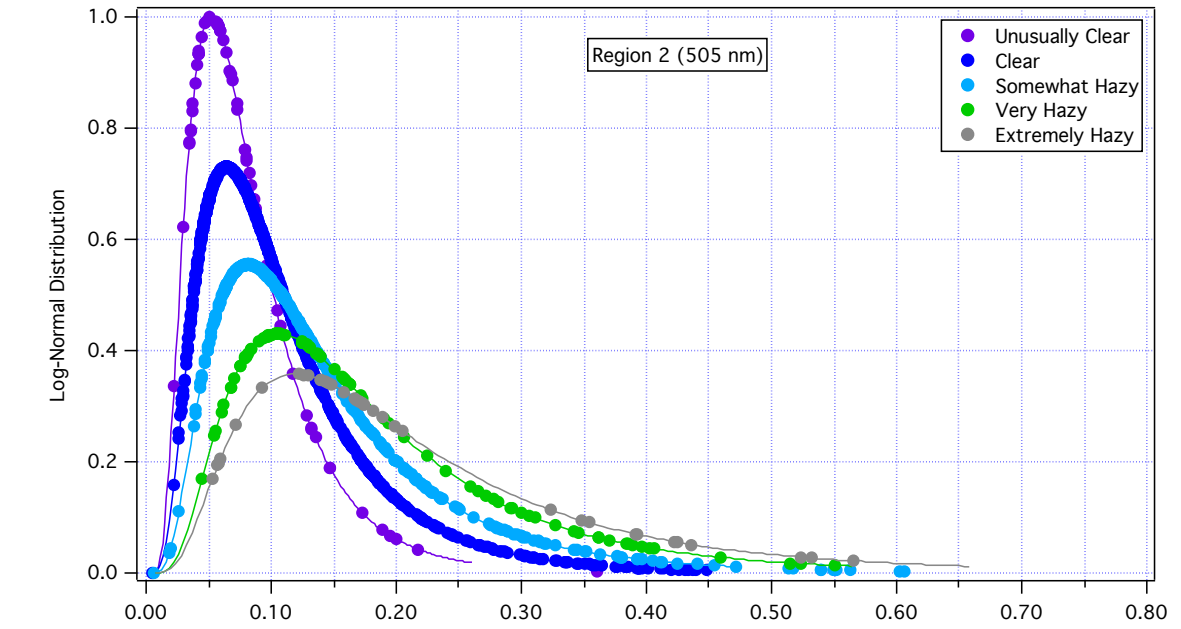


Table R12. Mean, standard deviation, and range for each visibility condition in Region 2

	$\mu$	$\sigma$	Range
Unusually Clear	0.09	0.06	0.03-0.14
Clear	0.11	0.08	0.03-0.19
Somewhat Hazy	0.15	0.11	0.04-0.26
Very Hazy	0.19	0.13	0.07-0.32
Extremely Hazy	0.23	0.15	0.08-0.37

Graph R12. Distribution of AOT for each matched pair in Region 2

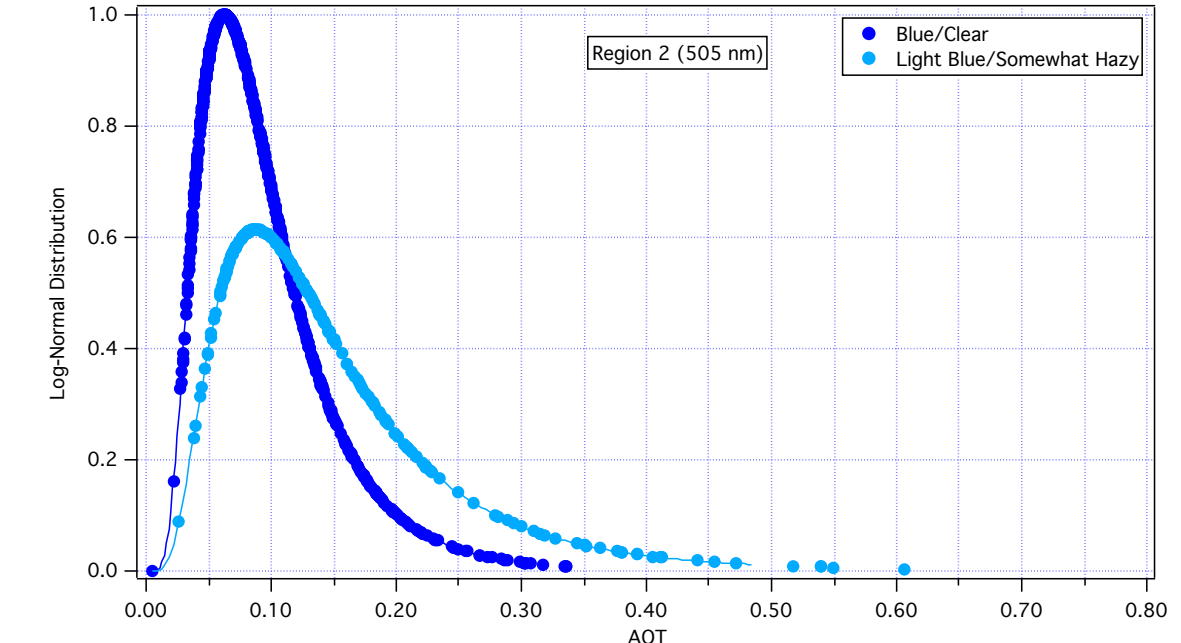


Table R17. Mean, standard deviation, and range for each matched pair in Region 2

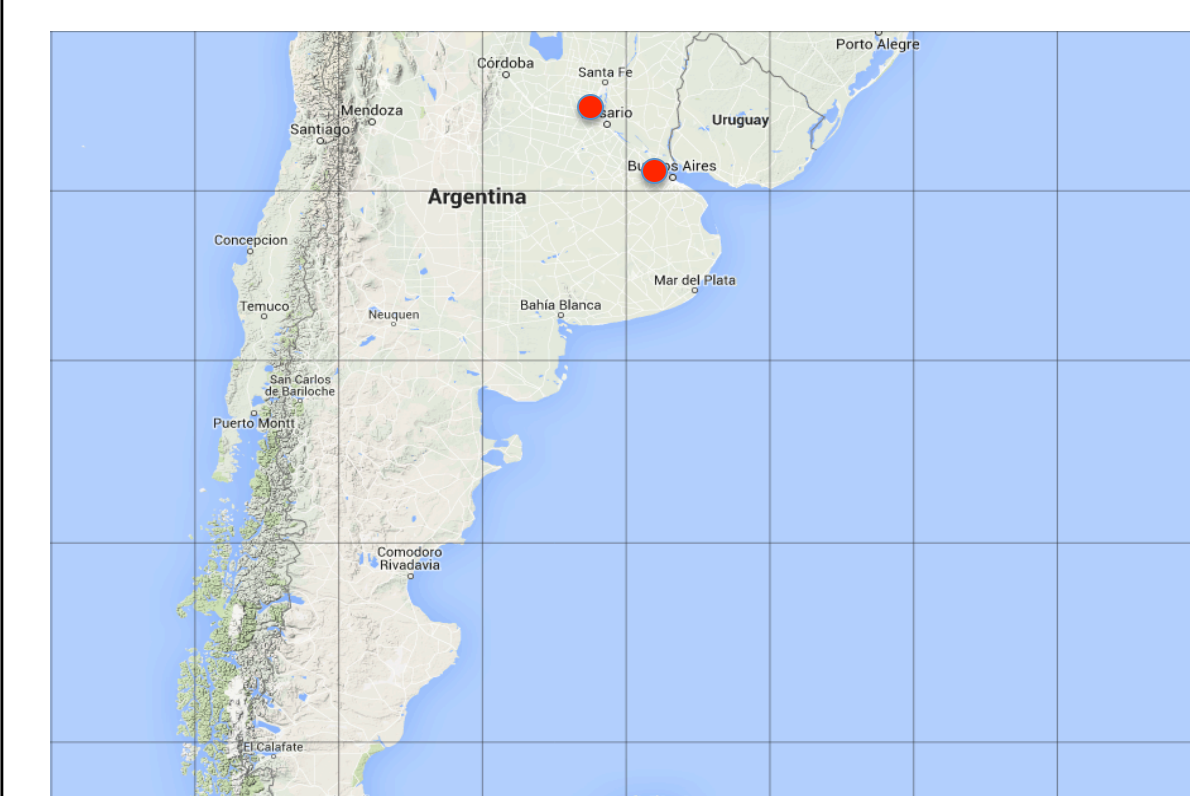
	$\mu$	$\sigma$	Range
Deep Blue/Unusually Clear	-	-	-
Blue/Clear	0.10	0.06	0.04-0.16
Light Blue/Somewhat Hazy	0.15	0.11	0.04-0.27
Pale Blue/Very Hazy	-	-	-
Milky/Extremely Hazy	-	-	-

### Region 2 Summary:

64% of data in matched pair category  
60% of data in clear visibility condition  
82% of data in “the box”

## Region 3

### Region Classification: South America



Sites: Escuela de Enseñanza Media 7 “Nicolas Copernico”, Escuela Primaria Particular Incorporada N°1345 (located in Argentina)

Table R3. Number of measurements for each sky color and visibility pairing in Region 3

Sky Color/Visibility	Deep Blue	Blue	Light Blue	Pale Blue	Milky
Unusually Clear	5	13	60	8	5
Clear	9	116	362	27	12
Somewhat Hazy	1	11	29	13	8
Very Hazy	0	2	8	5	1
Extremely Hazy	0	0	3	1	0

Graph R3. Distribution of AOT for each sky color condition in Region 3

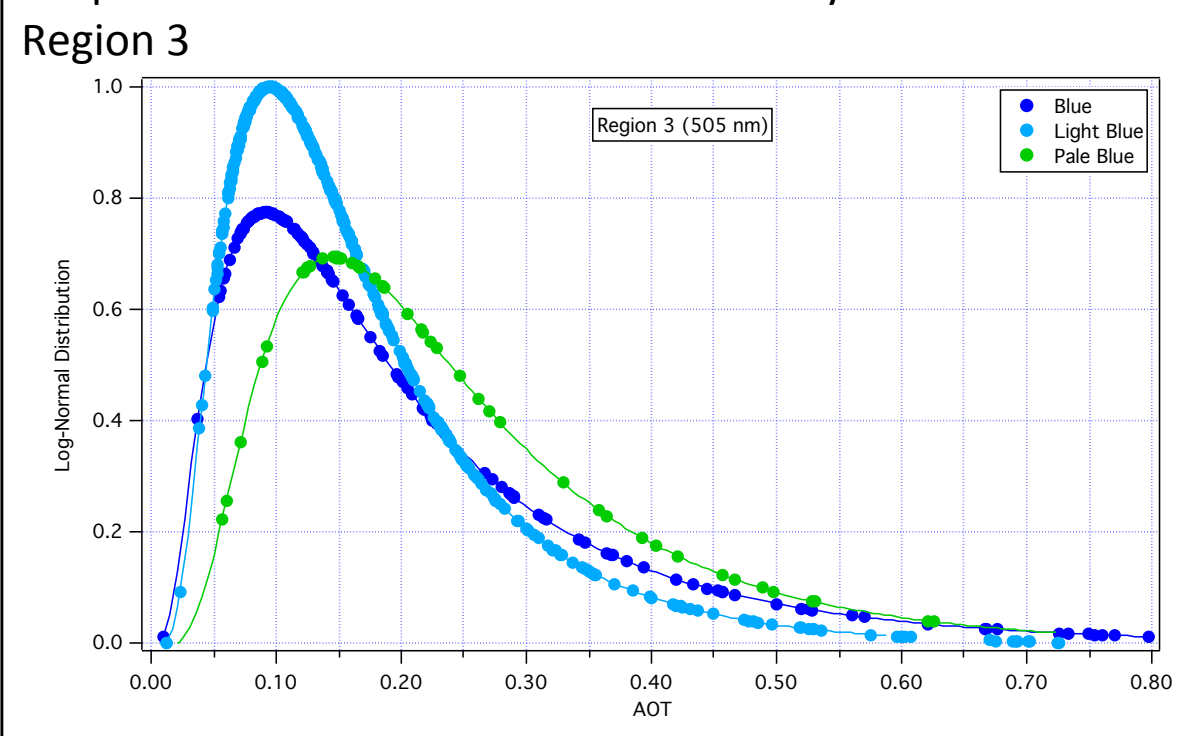


Table R8. Mean, standard deviation, and range for each sky color condition in Region 3

	$\mu$	$\sigma$	Range
Deep Blue	0.23	0.20	0.04-0.43
Blue	0.18	0.14	0.04-0.32
Light Blue	0.26	0.16	0.10-0.41
Milky	-	-	-

Graph R8. Distribution of AOT for each visibility condition in Region 3

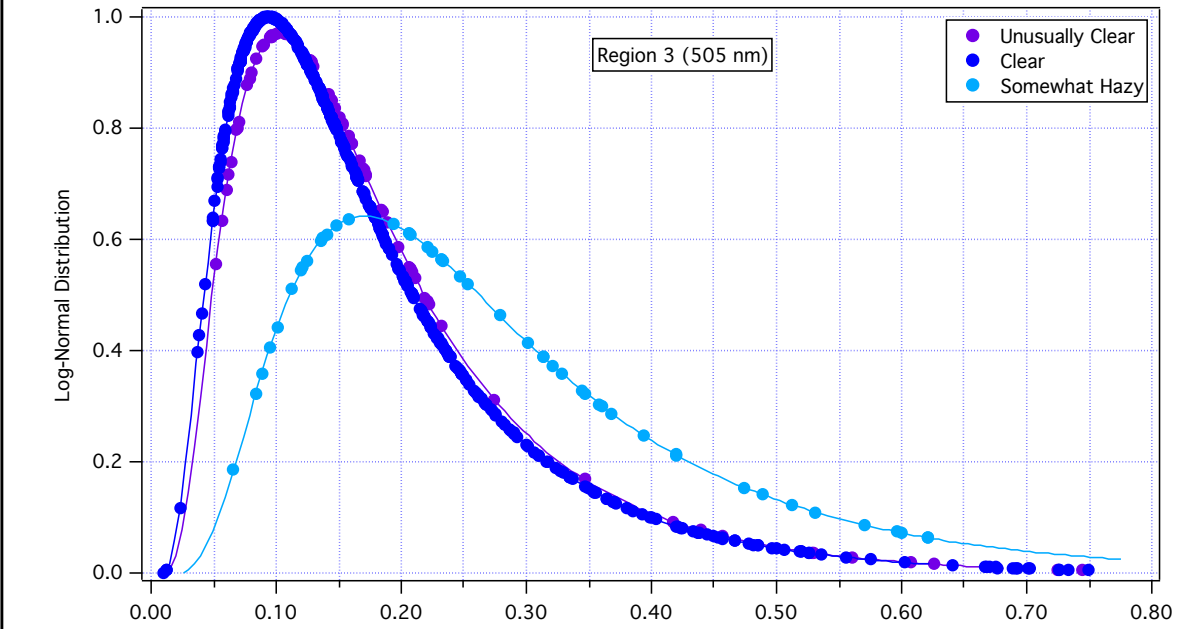


Table R13. Mean, standard deviation, and range for each visibility condition in Region 3

	$\mu$	$\sigma$	Range
Unusually Clear	0.20	0.16	0.04-0.36
Clear	0.19	0.15	0.04-0.34
Somewhat Hazy	0.29	0.16	0.13-0.46
Very Hazy	-	-	-
Extremely Hazy	-	-	-

Graph R13. Distribution of AOT for each matched pair in Region 3

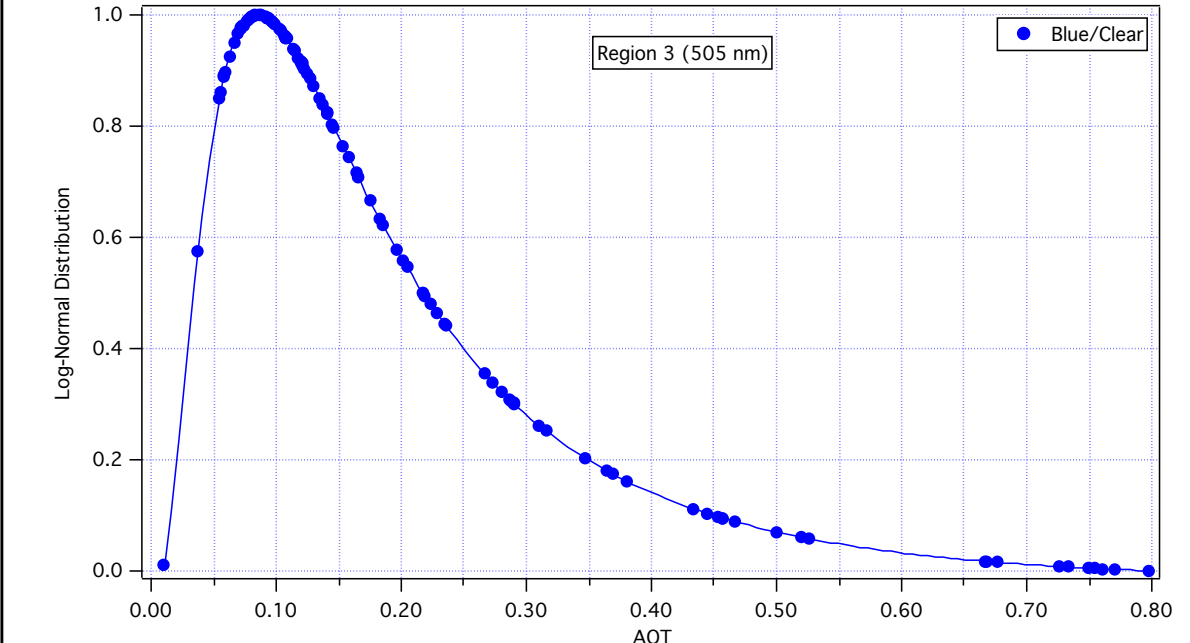


Table R18. Mean, standard deviation, and range for each matched pair in Region 3

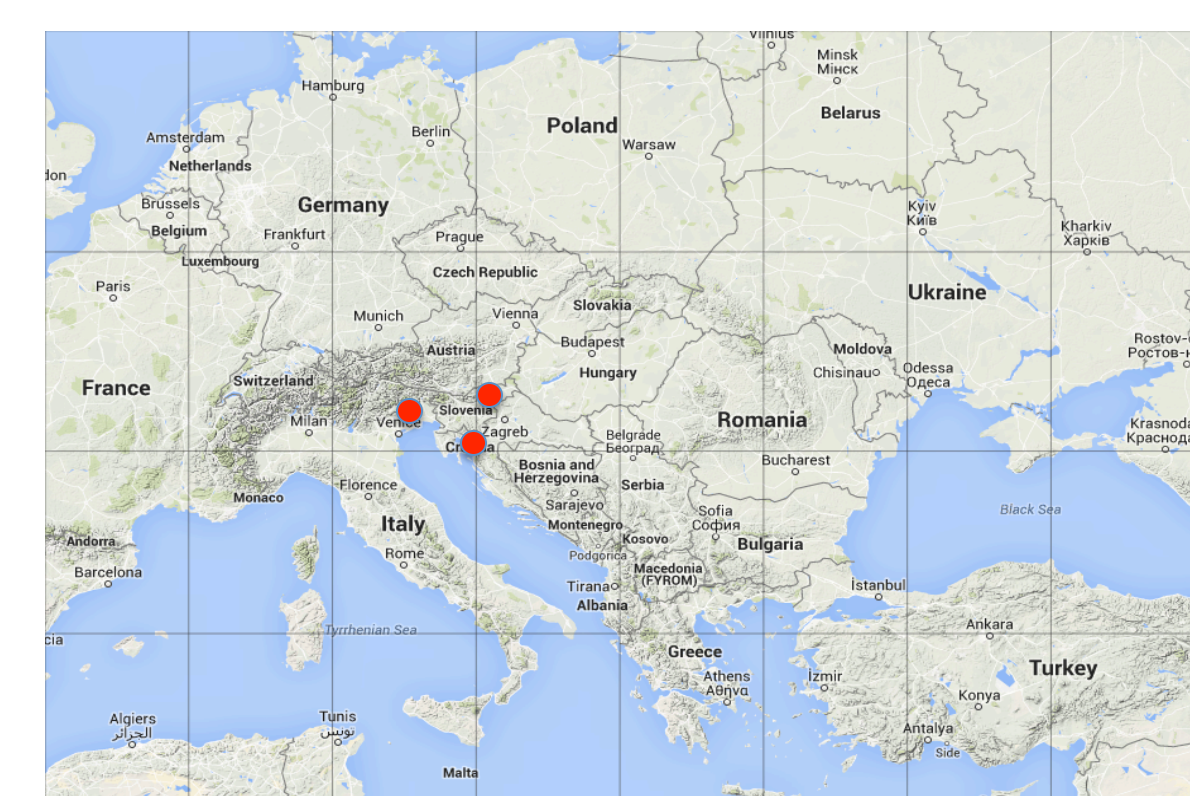
	$\mu$	$\sigma$	Range
Deep Blue/Unusually Clear	-	-	-
Blue/Clear	0.23	0.20	0.03-0.43
Light Blue/Somewhat Hazy	-	-	-
Pale Blue/Very Hazy	-	-	-
Milky/Extremely Hazy	-	-	-

### Region 3 Summary:

76% of data in matched pair category  
71% of data in clear visibility condition  
74% of data in “the box”

## Region 4

### Region Classification: Southern Europe



Sites: Istituto Tecnico Industriale Statale Malignani (located in Italy), Skola Za Medicinske Sestre Vrapce (located in Croatia), OS Matija Gubec (located in Croatia)

Table R4. Number of measurements for each sky color and visibility pairing in Region 4

Sky Color/Visibility	Deep Blue	Blue	Light Blue	Pale Blue	Milky
Unusually Clear	0	4	2	0	0
Clear	11	164	95	6	16
Somewhat Hazy	1	21	62	14	7
Very Hazy	0	0	3	2	5
Extremely Hazy	0	0	0	0	0

Graph R4. Distribution of AOT for each sky color condition in Region 4

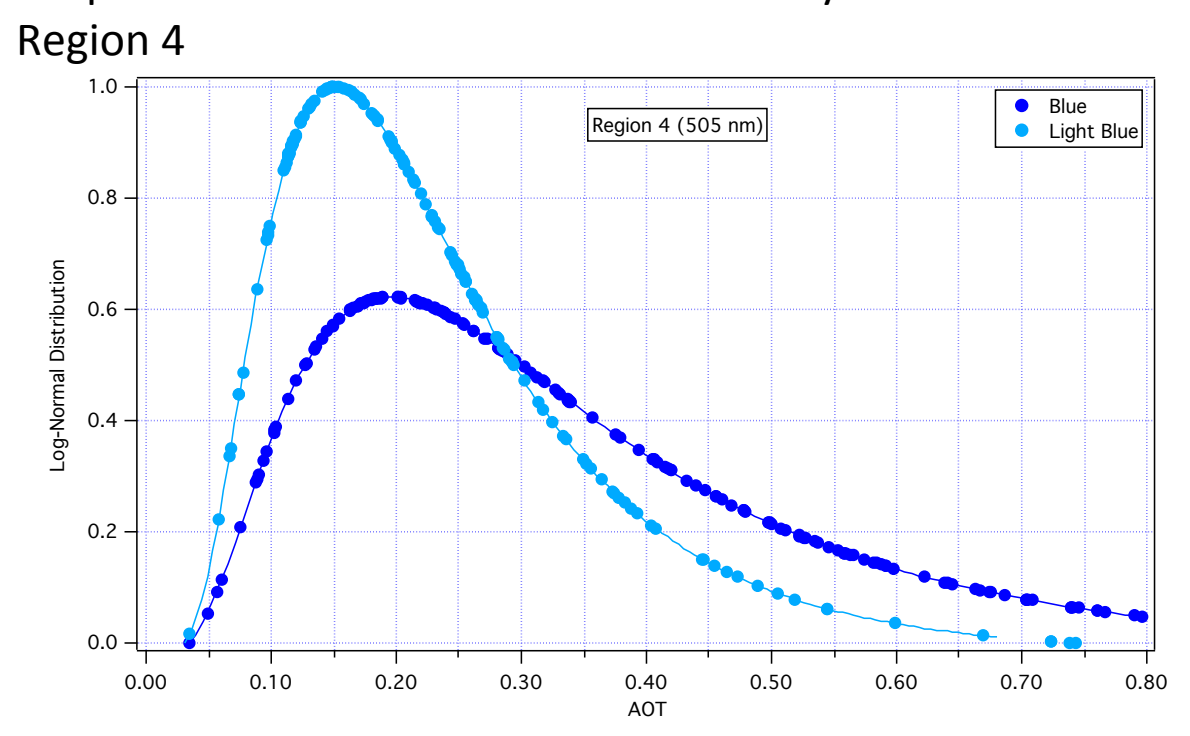


Table R9. Mean, standard deviation, and range for each sky color condition in Region 4

	$\mu$	$\sigma$	Range
Deep Blue	-	-	-
Blue	0.37	0.21	0.16-0.58
Light Blue	0.25	0.15	0.10-0.39
Pale Blue	-	-	-
Milky	-	-	-